

Exercise Ultrafast Computed Tomography for the Detection of Coronary Artery Disease

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Ultrafast computed tomography permits the assessment of global and regional left ventricular function during exercise. To evaluate the feasibility of using this new technique for the diagnosis of coronary artery disease, 27 patients undergoing cardiac catheterization for diagnosis of chest pain were evaluated. Fifteen patients had significant ($>50\%$) coronary artery stenosis by quantitative coronary angiography. One vessel disease was found in 12 patients and multivessel disease in 3. Fourteen (93%) of the 15 patients with significant coronary stenosis had a decrease in ultrafast computed tomographic ejection fraction during exercise from (mean \pm SD) $65 \pm 7\%$ to $60 \pm 7\%$ ($p < 0.001$). The tomographic ejection fraction increased $>5\%$ units during exercise in 10 (83%) of the 12 patients with normal coronary arteries. The mean tomographic ejection fraction in this group was $68 \pm 6\%$ at rest and $75 \pm 6\%$ at peak exercise ($p < 0.001$).

Regional wall motion was quantified by analyzing the

segmental ejection fraction of 12 30° pie segments at each tomographic level of the left ventricle. A new regional wall motion abnormality developed during exercise in 12 (86%) of 14 patients with coronary artery disease; one patient was excluded because of a technical problem in data storage. Eleven (93%) of the 12 patients with normal coronary arteries had normal wall motion during exercise. In no patient with ischemic heart disease were both variables, ejection fraction response and regional wall motion, normal.

Exercise ultrafast computed tomography appears to be a useful technique for the evaluation of coronary artery disease in patients with chest pain and predominant single vessel coronary artery disease. Quantitative assessment of the regional wall motion is a promising method for detecting abnormal wall motion produced by exercise-induced ischemia.

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Since Tennant and Wiggers (1) experimentally demonstrated that contraction abnormalities appear immediately after a reduction in coronary artery blood flow, analysis of wall motion has been used for the diagnosis of coronary artery disease. Assessment of left ventricular function and wall motion after exercise by radionuclide angiography has been widely used for this purpose (2-6). However, superimposition of cardiac chambers and the fact that only a single plane can be analyzed at one time are important limitations to an

accurate evaluation of regional wall motion and ejection fraction.

Recently developed ultrafast computed tomography has been used successfully to evaluate aortocoronary graft patency (7), myocardial perfusion (8,9) and acute myocardial infarction (10). Given its capability to obtain sequential images of the left ventricle throughout the cardiac cycle in multiple tomographic levels, left ventricular function and regional wall motion abnormalities can be readily evaluated at rest, during exercise or after pharmacologic interventions, as recently reported (11,12).

We report the first experience with the use of exercise ultrafast computed tomography for the diagnosis of coronary artery disease in patients undergoing diagnostic coronary angiography for evaluation of chest pain.

Methods

Study patients. The main purpose of this study was to analyze the value of ultrafast computed tomography in the

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diagnosis of chest pain syndromes in patients without past coronary events. We studied 31 patients undergoing cardiac catheterization, ventriculography and coronary arteriography for evaluation of chest pain. Patients with previous myocardial infarction diagnosed by electrocardiogram (ECG), a qualitatively abnormal ventriculogram, previous coronary bypass surgery or valvular or congenital heart disease were excluded from the study. There were 14 men and 17 women with a mean age of 52 ± 8 years (range 33 to 66). Patients underwent cardiac catheterization at Cook County Hospital and then were referred to the University of Illinois Hospital where exercise ultrafast computed tomography was performed. All patients gave informed consent under a protocol approved by the University of Illinois College of Medicine Institutional Review Board.

Cardiac catheterization. Each patient underwent routine cardiac catheterization, which included right and left heart pressure measurements, selective coronary arteriography and ventriculography. Angiograms of the coronary artery lesions were analyzed by Brown's method of quantitative coronary angiography (13). Each angiogram was projected and amplified to 20×22 cm. The outline of the most severe coronary lesion in each major coronary artery was traced in two orthogonal projections. The traced lesion's outline was digitized and computer-corrected for radiographic pin cushion and magnification distortion. The minimal cross-sectional area, maximal percent area stenosis, percent diameter stenosis in each projection and length of each lesion were calculated.

Exercise ultrafast computed tomography. All patients underwent exercise ultrafast computed tomography with the use of an Imatron C-100 scanner; the scanning technique has been described elsewhere (14). Patients were positioned supine in the scanner's couch, axially tilted 20° with the feet down and slewed 13° horizontally to the patient's right to approximate short-axis views of the left ventricle. The patient's chest was marked at the scanning plane to assure proper positioning during exercise. A small intravenous catheter (18 gauge) was inserted into an antecubital or external jugular vein. The circulation time was obtained in each patient with indocyanine green and an ear densitometer so that the arrival time of contrast medium in the left ventricle could be estimated (15). After a bolus injection of 25 to 35 ml of contrast medium (Renografin-76), scans were obtained with the use of a movie protocol that scans one target repetitively for one cardiac cycle at a rate of 17 scans/s triggered by the ECG. The contrast medium was injected at the rate of 10 ml/s. With the use of two or three targets in sequence, four or six 8 mm thick levels were scanned. A second scanning sequence was performed to evaluate at least eight levels of the left ventricle at rest.

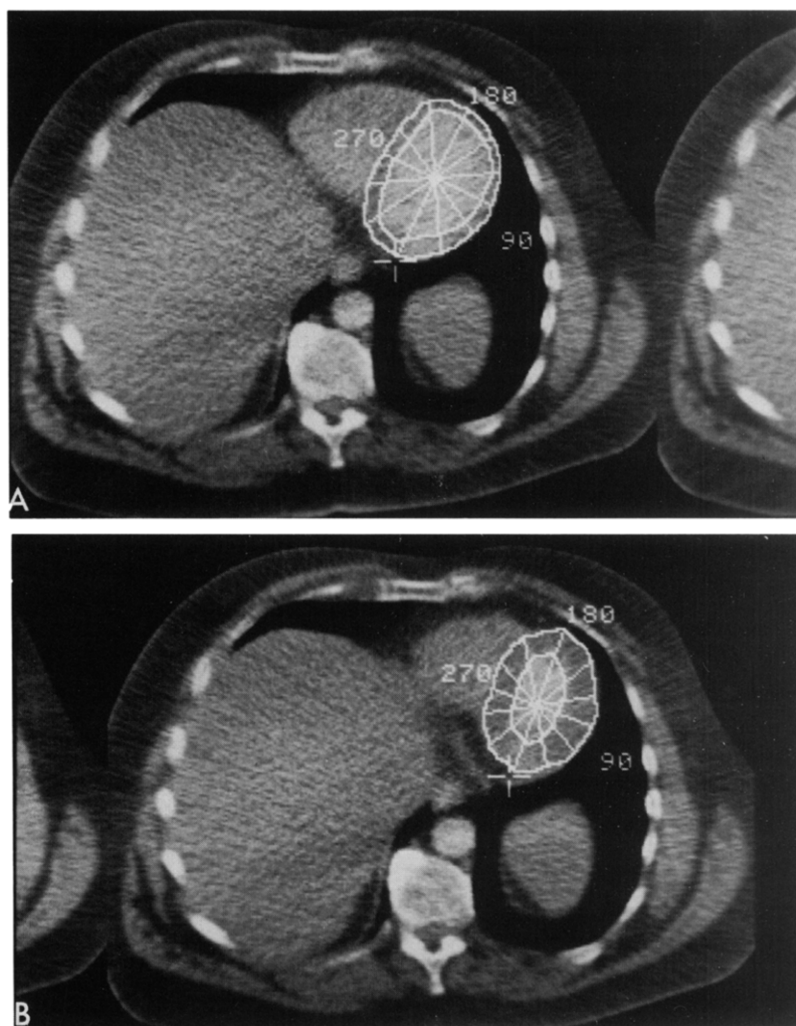
Symptom-limited exercise was performed with the use of a bicycle ergometer attached to the scanner couch while increasing the resistance 25 W-s every 2 min. A precordial

ECG lead approximating lead V_5 was monitored continuously through the test. Before the end of the exercise, the patient's position in relation to the scanning beam was rechecked against the reference point on the chest to assure that the levels imaged during exercise were the same as those imaged during the rest study. Another circulation time was determined and then eight levels of left ventricle were scanned with use of the movie protocol. Once the patient developed symptoms, exercise was continued for 30 s to 1 min to obtain all measurements during peak exercise. The skin entry radiation dose is approximately 325 millirads per slice. Therefore, each patient was exposed to approximately 9 to 9.75 rads for the protocol described. The cross-sectional images of the left ventricle obtained by this protocol were later displayed for analysis on a television console. Exercise ultrafast computed tomography was performed within 1 month of coronary angiography and interpreted without knowledge of the angiographic results. Six patients were being treated with a beta-adrenergic blocker, four with a beta-blocker and a calcium antagonist and nine with a calcium antagonist and a nitrate. Drugs were not discontinued before the exercise tomographic procedure.

Left ventricular ejection fraction. Rest and exercise studies were analyzed with use of a computerized regional wall motion analysis program. Each cross-sectional image of the left ventricle from the base to the apex was analyzed by tracing the inner boundaries of the left ventricular wall at end-systole and end-diastole excluding the papillary muscles (Fig. 1). Thus, the ejection fraction and end-diastolic and end-systolic volumes were calculated at each tomographic level. By summing volumes of each tomographic level, the global ejection fraction was calculated at rest and during exercise (Table 1). Only comparable levels were used to compute the rest and exercise ejection fraction. Occasionally, small portions of the base or apex of the left ventricle were missing in either the rest or the exercise study and were excluded from the computation of the rest and exercise ejection fraction. The ejection fraction was considered abnormal during exercise if it failed to increase 5% units above the rest value (16).

Wall motion analysis. Quantitative analysis of the wall motion was also done with a computerized program. Subsegmental ejection fraction was calculated by selecting a reference point in the mid-posterior wall after the inner and outer boundaries of the left ventricular wall at end-systole and end-diastole were traced and computer-generated radii placed counterclockwise every 30° . An endocardial end-diastolic centroid was used for the origin of the radii for both the end-systolic and end-diastolic images (12) (Fig. 1). The segments involving the mitral and aortic valves were excluded from the analysis. The lateral wall was represented by the segments between 60° and 150° , the anteroapical wall by the segments between 150° and 300° and the posterior wall by the segments from 300° to 60° . Corresponding cross-

Figure 1. Cross-sectional image of contrast-enhanced mid left ventricle at end-diastole (A) and end-systole (B). The outer and inner boundaries of the ventricular wall, the reference point (0°) and the 12 radii are shown.



sectional images of the left ventricle were analyzed at rest and during exercise. Internal left ventricular landmarks (aortic valve, mitral valve, anterolateral papillary muscle,

posteromedial papillary muscle and apex) were used to assure that appropriate levels were compared between rest and exercise. To compare different segments within the same patient and results among different patients, the ejection fraction of each segment was normalized with use of the following formula:

Table 1. Global and Segmental Ejection Fractions in a Representative Patient

Ventricular Level	End-Diastolic Volume (ml)	Stroke Volume (ml)	Ejection Fraction (%)
1	14.8	12.6	85
2	19.2	15.4	80
3	31.6	20.8	65
4	33.3	20.7	62
5	15.7	11.3	71
6	17.1	12.9	75
7	21.8	18.1	83
8	13.9	11.6	83
9	7.9	7.4	94
10	3.5	3.4	98
Global	178.9	134.3	75

$$\text{Normalized ejection fraction (EF)} = \frac{\text{segmental EF} - \text{global EF}}{\text{global EF}}$$

Data from 615 segments at rest and 619 segments during exercise were analyzed in the 12 patients with normal coronary arteries. Slightly fewer segments were analyzed at rest than during exercise because of minor differences in the effect of the mitral and aortic valve on wall motion. The mean normalized ejection fraction for all segments in this group was 0.02 ± 0.30 and 0.03 ± 0.27 SD at rest and during exercise, respectively. A segment was considered to have abnormal contraction when the normalized segmental ejection fraction decreased below 2 SD from the mean for all

segments. Therefore, any segment was considered abnormal when the normalized ejection fraction declined below -0.58 at rest and -0.51 during exercise. Regional wall motion abnormalities were diagnosed when an abnormal normalized ejection fraction was found in at least two contiguous pie segments within a level and at least one contiguous pie segment in an adjacent tomographic level of the left ventricular wall; therefore, for a patient to be diagnosed as demonstrating a wall motion abnormality, at least three contiguous pie segments had to be abnormal.

ECG stress test. Treadmill exercise was performed at Cook County hospital before coronary angiography following the Bruce protocol. Exercise was stopped if the patient developed symptoms or ST segment depression ≥ 2 mm or a decrease in blood pressure. A positive test was diagnosed if there was ≥ 1 mm of straight or downsloping ST segment depression beyond baseline.

Thallium-201 myocardial scintigraphy. At peak exercise the patient received an intravenous injection of 2.5 to 3 mCi of thallium-201. Every effort was made to have the patient continue to exercise for 1 min after injection. The patient was then imaged within 10 min of the end of exercise in the anterior, 30° right anterior oblique and 60° left anterior oblique views with use of a Siemens Scintiview large field view camera. Four hour redistribution images were obtained if any abnormalities were seen on the immediate postexercise images. A perfusion deficit was determined by visual examination of each image photographed on conventional X-ray film. All scans were interpreted by an experienced nuclear medicine specialist.

Statistical analysis. All mean data are expressed as mean \pm SD. Differences between group means were analyzed with use of an unpaired *t* test and changes between rest and exercise values with use of a two-sided paired *t* test. A chi-square analysis was used to compare qualitative samples.

Results

Coronary anatomy. Fifteen patients had significant ($>50\%$) reduction in the diameter of one or more coronary arteries (Table 2). Single vessel disease was found in 12 patients and multivessel disease in 3. Among patients with single vessel disease, the left anterior descending artery was involved in eight cases, the left circumflex artery in one and the right coronary artery in the remaining three. The left circumflex and right coronary arteries were both involved in two cases and the left anterior descending and right coronary arteries in one. One patient with 57% and 56% stenoses of the right and circumflex coronary arteries, respectively, also had a 73% stenosis of a diagonal branch of the left anterior descending artery.

A 100% obstruction of a major coronary artery was found in four cases, involving the left circumflex artery in one and

the left anterior descending artery in the remaining three. This occluded vessel was totally opacified by collateral flow from the right coronary artery in each case.

Normal coronary arteries were found in 16 patients (11 women and 5 men).

Exercise Ultrafast Computed Tomography

Exercise. Ten of the 15 patients with coronary artery disease and 5 of the 12 with normal coronary arteries developed chest pain during exercise ultrafast computed tomography ($p < 0.05$). The heart rate increased from 67 ± 9 to 104 ± 10 beats/min in patients with coronary artery disease and from 76 ± 11 to 114 ± 18 beats/min in patients without coronary artery disease; the exercise duration was 8 ± 3 min (range 5 to 13) and 9 ± 3 min (range 5 to 16), respectively. The work load achieved was 48 ± 18 W-s in patients with coronary artery disease and 50 ± 23 W-s in patients without coronary artery disease. Patients with normal coronary arteries achieved a higher heart rate and work load and exercised longer than did patients with coronary artery disease, but no statistical differences were found.

Ejection fraction. Rest ejection fraction was normal in all 27 patients, ranging from 50% to 79%. In four other patients without coronary artery disease, the global ejection fraction could not be calculated during exercise because of improper positioning of the patient in the scanner. These four patients are excluded from further analysis. The mean rest ejection fraction of the 12 patients without coronary artery disease was $68 \pm 6\%$ and the mean at peak exercise was $75 \pm 6\%$ ($p < 0.001$) (Fig. 2). In 10 (83%) patients the ejection fraction increased $\geq 5\%$ units over the rest value and the mean percent increase was $7 \pm 4\%$ units in this subgroup. Of the remaining two patients, one had a $<5\%$ units increase and no change was observed in the other; neither patient was taking a beta-blocker.

The mean ejection fraction at rest of the 15 patients with coronary artery disease was $65 \pm 7\%$. During exercise, the ejection fraction decreased in 14 patients (93%) with a mean ejection fraction during exercise of $60 \pm 7\%$ ($p < 0.001$). The mean percent decrease of the ejection fraction was $7 \pm 3\%$ units. Only one patient with coronary artery disease had an increase in ejection fraction during exercise. Patients with $>70\%$ left anterior descending stenosis had a greater decline in exercise ejection fraction than their counterparts (-10 ± 4 versus $-3 \pm 7\%$ units, $p < 0.05$). The presence of a beta-blocker did not appear to alter the exercise ejection fraction response observed; in the five patients with coronary artery disease taking a beta-blocker, the ejection fraction decreased during exercise, whereas it increased in the five patients without coronary artery disease who were taking a beta-blocker.

The intraobserver variability for tracing the endocardial border of the left ventricle was assessed by measuring the

Table 2. Results of Exercise Ultrafast Computed Tomography Compared With Results of Quantitative Coronary Angiography and Other Stress Tests in 15 Patients With Coronary Artery Disease

A. Exercise Ultrafast Computed Tomography					B. Quantitative Coronary Artery Disease						C. Other Stress Tests	
Patient No.	Levels Analyzable	EF (%)	No. of Abnormal Segments During Exercise	Size of Abnormal Segmental Changes (°)	Patient	Vessel	% Stenosis		Minimal Diameter (mm)	Minimal Area (mm ²)	Treadmill ECG Results	Thallium-201 Results
							By Diameter	By Area				
1	4	-9	3	0 to 60 330 to 360	1	LCx	100				+	+
2	3	-8	7	60 to 120	2	LAD	100				+	+
3	7	-5	1	300 to 330	3	RCA	76	94	0.81	0.51	0	0
4	5	-19	4	120 to 240	4	LAD	88	98	0.18	0.02	-	+
5	6	+11	—	—	5	LCx	56	80	0.70	0.38	-	0
						RCA	57	82	0.72	0.41		
						Diag.	73	93	0.30	0.07		
6	7	-9	9	0 to 30 240 to 360	6	RCA	93	99	0.15	0.02	-	0
7	4	-9	7	150 to 300	7	LAD	100				-	+
8	6	-10	8	150 to 300	8	LAD	81	96	0.41	0.13	-	-
9	7	-4	10	0 to 60 270 to 360	9	LCx	100				0	0
						RCA	74	93	0.62	0.30		
10	5	-10	3	180 to 270	10	LAD	88	98	0.22	0.04	+	+
11	5	-7	2	180 to 240	11	LAD	74	93	0.46	0.16	-	-
12	6	-1	3	120 to 180	12	LAD	64	87	1.09	0.93	0	0
						RCA	67	89	0.63	0.31		
13	5	-6	5	180 to 270	13	RCA	74	93	0.56	0.24	+	0
14	7	-7	5	150 to 210	14	LAD	100				+	0
15	5	-10	11	150 to 300	15	LAD	97	99	0.06	0.01	0	0

+ = positive; - = negative; 0 = not done; CAD = coronary artery disease; Diag. = diagonal branch; ECG = electrocardiographic; EF = ejection fraction; LAD = left anterior descending coronary artery; LCx = left circumflex coronary artery; RCA = right coronary artery.

global ejection fraction at rest of all patients on 2 different days. The percent difference of each ejection fraction was calculated from the difference of that determination and the average of the two ejection fractions measurements. The intraobserver variability, calculated as the mean \pm SD of percent differences, was $1.46 \pm 1.05\%$ units.

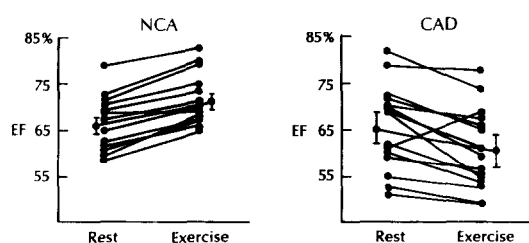
Regional wall motion. The quantitative method for the analysis of the left ventricular wall motion was done in 26 of the 27 patients. In one patient with coronary artery disease, quantitative analysis could not be performed because of a technical problem with the data storage. Initial qualitative

assessment of this patient's regional wall motion by two independent observers had noted a definite regional abnormality in cephalad levels of the anterior wall during exercise.

With use of the quantitative method described, the regional left ventricular contraction in normal subjects was found to be somewhat heterogeneous at rest. The distribution of the normalized segmental ejection fractions of patients with normal coronary arteries is shown in Figure 3. The heterogeneity is presented by the spread of the distribution. This spread decreased during exercise in patients with normal coronary arteries. Regional wall motion was defined as abnormal at rest, by the criteria described, in two patients without and in three patients with coronary artery disease. The defined abnormal contraction pattern became normal during exercise in those patients without coronary artery disease but worsened in those with coronary artery disease.

Twelve (86%) of the 14 analyzable patients with coronary artery disease and one patient without coronary artery disease, developed regional wall motion abnormalities or worsening of rest abnormalities during exercise (Table 2). Regional wall motion became abnormal in the anteroseptal region during exercise in eight (89%) of nine patients with significant left anterior descending lesions. Figure 4 shows a

Figure 2. Individual values of the global ejection fraction (EF) and the mean values at rest and during exercise of the 12 patients with normal coronary arteries (NCA) (left) and the 15 with coronary artery disease (CAD) (right).



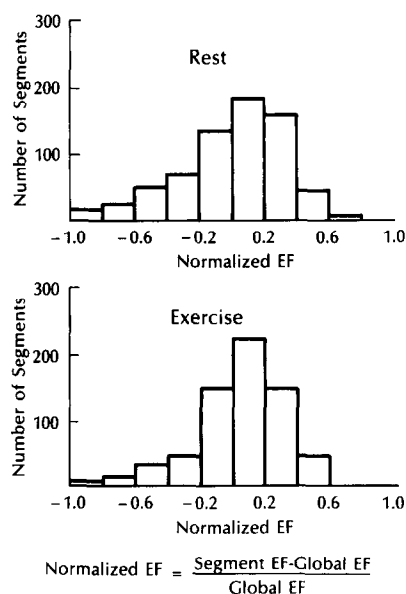


Figure 3. The distribution of the normalized segmental ejection fraction (EF) of the 12 patients with normal coronary arteries at rest (**top**) and after exercise (**bottom**). The heterogeneity of the left ventricular contraction is represented by the spread of the normalized ejection fractions.

normal distribution of normalized segmental ejection fractions of the anteroapical wall segments at rest in one such patient. Four segments became abnormal during exercise as represented by normalized ejection fraction values < -0.51 . In one patient with a single left circumflex artery lesion and one with combined right and circumflex artery lesions, the posterior wall developed an abnormal contraction pattern during exercise. Isolated right coronary artery stenosis was present in three patients, and two showed abnormal regional contraction of the inferior portion of the interventricular septum.

No patient with coronary artery disease had both a normal ejection fraction and a normal regional wall motion response to exercise. Conversely, no patient with normal coronary arteries had both an abnormal ejection fraction and an abnormal wall motion response to exercise. Therefore, results in 12 of the 27 patients could be categorized as definitively abnormal, in 9 as definitively normal and in 6 as uncertain.

Treadmill tests. Nineteen (70%) of the 27 patients undergoing exercise ultrafast computed tomography also underwent a treadmill stress test (Table 2). The ECG response was abnormal in 5 (45%) of 11 with angiographic coronary disease and normal in 4 (50%) of 8 with normal coronary arteries. Ten patients (37%) also underwent thallium-201 myocardial scintigraphy (Table 2). The scan was interpreted as abnormal in 5 (71%) of 7 patients with abnormal coronary angiography and normal in 2 (68%) of 3 patients with normal coronary arteries.

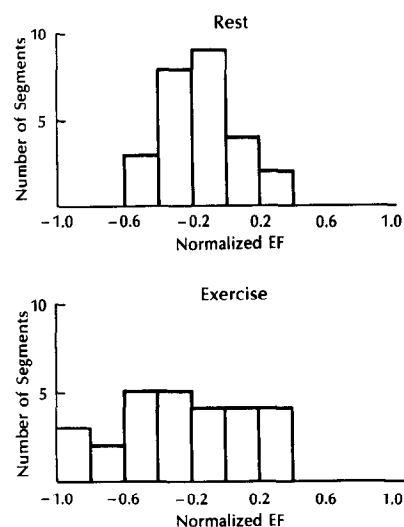


Figure 4. Distribution of the normalized segmental ejection fraction (EF) of the anterior wall segments of a patient with an 88% left anterior descending coronary artery stenosis. A normal contraction pattern is observed at rest (**top**), becoming abnormal during exercise (**bottom**) represented by the abnormal normalized segments at the left of the distribution.

Discussion

Physiologic assessment of the functional importance of coronary artery stenosis by noninvasive methods has been attempted by a variety of methods. Evaluation of regional and global left ventricular function by radionuclide angiography during stress has emerged as one of the most useful methods for this purpose. Initial data indicated that radionuclide angiography had a high accuracy for the diagnosis of coronary artery disease (17-19). However, more recent reports (6,20,21) evaluating larger numbers of patients have shown a lower sensitivity and specificity.

Recently developed ultrafast computed tomography, with 50 ms scanning capability, can obtain 8 mm thick cross-sectional images of the left ventricle throughout the cardiac cycle. By evaluating adjacent tomographic levels, from the apex to the base of the heart, one can calculate the global ejection fraction and perform quantitative analysis of wall motion. The amount (25 to 35 ml) and the route (intravenous) used for the contrast medium given for ventriculography produce insignificant hemodynamic changes, particularly when ventricular function is evaluated in the first several cardiac cycles after the contrast medium reaches the left ventricle (22). The rapid acquisition time of ultrafast computed tomography permits scans to be obtained for eight levels in seven cardiac cycles; therefore, the analysis of ventricular function is unlikely to be altered by any hemodynamics changes induced by contrast medium (23). A previous report (24) has shown a good correlation ($r = 0.91$) between the ejection fractions calculated by biplane contrast angiography and ultrafast computed tomography.

This report is the first evaluating the feasibility of exercise ultrafast computed tomography for the diagnosis of ischemic heart disease in patients presenting with chest pain and no previous myocardial infarction.

Ejection fraction. An increase in the ejection fraction of $\geq 5\%$ units during exercise has been widely used to characterize a normal response to exercise. This ejection fraction response evaluated by exercise radionuclide angiography clearly identified patients with coronary artery disease in the initial reported series (17). However, a lower sensitivity and specificity for the test has been reported more recently (6,20,21,25). Ejection fraction at rest is highly predictive of the ejection fraction change during exercise; the lower the rest ejection fraction the lesser the degree of the ejection fraction change after exercise (3,26). Presumably, the decrease in ejection fraction during exercise depends on the amount of myocardium rendered ischemic. In our series, all patients had a normal ejection fraction at rest and it decreased during exercise in 14 of the 15 patients with coronary artery disease. In the only patient with coronary artery disease whose ejection fraction increased during exercise the anterior wall motion was qualitatively abnormal during exercise (Patient 5, Table 2).

The ejection fraction failed to increase $>5\%$ units during exercise in two patients without coronary artery disease. One of them exercised only at a low level; the cause in the other is unexplained. However, none of the 12 patients without coronary disease had a decrease in ejection fraction during exercise. Although, variations in the ejection fraction response to exercise in patients with chest pain and normal coronary arteries have been reported (25,27), exercise ultrafast computed tomography demonstrated a remarkably uniform good response. Population differences, unrecognized coronary stenosis, exercise-induced coronary vasospasm, intrinsic myocardial disease and a pretest referral bias may be important causes for these differences. Lower sensitivity for exercise ejection fraction response has been reported (28) during beta-blocker therapy; however, beta-blockers did not appear to alter the response in our patients.

The measurement of left ventricular function during exercise by radionuclide angiography, by either the first pass or the gated-equilibrium technique, has some limitations (29). In particular, complete separation of all cardiac chambers throughout the cardiac cycle cannot be achieved with the radioisotope technique, so the precise delineation of the region of interest (left ventricle) and background subtraction depends on the experience of the observer. Ultrafast computed tomography is a minimally invasive technique, requiring only a small amount of contrast medium for the complete enhancement of all cardiac chambers. The spatial resolution is excellent and the tomographic display obviates problems of overlying structures. However, appropriate timing of the arrival of the contrast material to the left ventricle is needed for optimal visualization. The fast acquisition time of the

ultrafast computed tomographic scanner assures that images of the whole left ventricle throughout the cardiac cycle can be obtained in a few seconds. Thus, ventricular function can be evaluated at eight adjacent tomographic levels within seven cardiac cycles at peak exercise.

Regional wall motion. Regional ventricular dysfunction induced by stress is a very specific indicator of ischemia. The reported specificities using radionuclide angiography vary from 70% to 100% (17,30). However, the criteria for diagnosing regional wall motion abnormalities vary from investigator to investigator and significant experience is required for the correct qualitative evaluation of regional wall motion (31). To improve the reproducibility of radionuclide angiography for the assessment of wall motion, several quantitative methods have been developed (32,33); however, most of them are somewhat complex and have not yet supplanted qualitative visual evaluation by trained observers. Regional wall motion abnormalities have also been quantified by contrast ventriculography with several methods, but differences among methods and inter- and intraobserver variability are significant (34-36), and the invasive nature of cardiac catheterization makes the performance of exercise difficult. In addition, contrast ventriculography with cinefluoroscopy is a planar imaging method, thereby creating the possibility of missing regional wall motion abnormalities even if biplane techniques are employed.

Quantitative assessment of regional wall motion by ultrafast computed tomography was previously reported by Feiring et al. (12) in animals and normal humans. The degree and extent of wall motion abnormalities in patients with coronary artery disease can also be quantified by this method, as shown in this study. Segmental ejection fractions at rest are somewhat heterogeneous in the normal ventricle but become more homogeneous after exercise (Fig. 3). This phenomenon has also been observed with the use of ultrafast computed tomography in normal volunteers after dobutamine infusion (37). This regional asynchrony of left ventricular contraction in normal subjects has also been reported with two-dimensional echocardiography (38). The fact that some of our patients with normal coronary arteries had abnormal segmental ejection fractions at rest that became normal during exercise is probably due to this heterogeneity. The quantitative criteria used in this study to define abnormal wall motion separate well the patients with coronary artery disease from those with normal coronary arteries. Thus, 12 of 14 patients with coronary artery disease had areas of abnormal regional wall motion during exercise that correlated with a significant stenosis in the coronary artery supplying that region. The two remaining patients had an abnormal ejection fraction response to exercise even though a regional wall motion abnormality was not identified.

Use of ultrafast computed tomography for analysis of regional wall motion during exercise has the advantage over the use of radionuclide angiography in that all ventricular

walls are well visualized and no adjustments for background need to be made. Wall motion can be analyzed for 12 segments in each cross-sectional image of the left ventricle by ultrafast computed tomography, thereby providing extremely detailed information. However, it is very important to obtain a good short-axis view during exercise for the accurate evaluation of wall motion. Positioning of the patient so the posterior wall is as perpendicular as possible to the scanning beam is particularly important to minimize errors due to partial voluming. The tip of the apex of the left ventricle may not be well evaluated when it is assessed in the short-axis view, but wall motion abnormalities of this region are usually associated with abnormalities of the anterior or inferior wall as well.

Assessment of wall motion by ultrafast computed tomography requires less contrast medium than does conventional contrast ventriculography and the contrast medium can be injected into a superficial peripheral vein. Also, adjacent tomographic levels of the entire left ventricle can be obtained by ultrafast computed tomography, whereas only two planes per injection can be imaged by conventional ventriculography.

Although not all patients having exercise ultrafast computed tomography had a treadmill exercise test and even fewer had thallium-201 myocardial scintigraphy, in those patients who did, the results suggest that exercise ultrafast computed tomography provides better separation between patients with and without coronary artery disease.

Limitations. This study demonstrates that exercise ultrafast computed tomography is a feasible technique for assessing coronary artery disease. However, our results may be influenced by a pretest referral bias, as we evaluated patients predominantly with single vessel disease (75%) and chest pain. These facts may favor the development of a positive test as opposed to what might occur in patients with single vessel disease and no symptoms. Therefore, our apparent high sensitivity may be influenced by the fact that we selected only patients with chest pain and our results may not be applicable to all patient groups with coronary artery disease. Sixteen percent of patients (4 of 31) had unanalyzable exercise studies. However, after an appropriate learning curve it is likely there would be fewer unanalyzable studies.

Conclusions. Exercise ultrafast computed tomography correctly diagnosed the presence of significant coronary artery disease when both variables, ejection fraction response and wall motion analysis, were abnormal during exercise. The combination of a normal ejection fraction and normal wall motion response to exercise also correctly predicted normal coronary arteries. However, a single abnormality of ejection fraction or wall motion was observed in three patients with coronary artery disease and in three with normal coronary arteries and in these circumstances further diagnostic studies are necessary. Therefore, exercise ultra-

fast computed tomography shows promise as a useful technique for detecting significant coronary artery disease in patients with chest pain, even when only single vessel disease is present. However, further studies with larger numbers of patients and other pretest selection criteria are necessary before the total value of this diagnostic test can be understood. Exercise ultrafast computed tomography does provide for the evaluation of myocardium at jeopardy and the assessment of left ventricular function reserve. Also, the quantitative assessment of regional wall motion by ultrafast computed tomography is a promising method for the accurate and reproducible analysis of left ventricular contraction.

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